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Influence of the Portuguese Bend landslide on the character of the effluent-affected sediment deposit, Palos Verdes margin, southern California

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Abstract

Historic accretion of sediment on the Palos Verdes margin off Los Angeles County, CA, is dominated by two sources, effluent from Whites Point outfall and sediment eroded from the toe of Portuguese Bend landslide. In this paper, we document the recent history of sedimentation from these non-marine sources from 1937 until the late 1990s, and attempt to estimate the amount of material preserved on the shelf. Toward that end, we characterized offshore sediment by physical and geotechnical testing, using non-destructive gamma-ray whole-core logging techniques and conventional geotechnical strength tests, and X-ray diffraction. Results are reported within a geographic information system framework that allows for: (1) the evaluation of the spatial variability of the measured properties, and (2) assessment of the influence of these properties on processes affecting the effluent-affected sediment layer. In the inner shelf, material eroded by wave action from the toe of the Portuguese Bend landslide since 1956 has contributed 5.7–9.4 million metric tons (Mmt) of sediment, from a total eroded mass of 12.1 Mmt. A lesser fraction ($\geqslant$2.7 Mmt) of sediment is incorporated into the mid- and outer-shelf effluent-affected sediment layer. Evidence from X-ray diffractograms clearly indicates that landslide material has mixed with the mid- and outer-shelf effluent. From 1937–1987, it is estimated that 3.8 Mmt of solid anthropogenic effluent was discharged into the water column and onto the Palos Verdes Shelf. Published by Elsevier Science Ltd.

1. Introduction

The Palos Verdes Peninsula is composed of seaward-dipping siliceous shales and volcanic rocks of the Altamira member of the Miocene Monterey Formation (Vonder Linden and Lindvall, 1982). Rapid uplift of the peninsula, evident in 17 preserved wave-cut marine terraces, 13 of them exposed above sea level, has resulted in rugged coastal terraces, steep slopes and bathymetry, and a preponderance of ancient and active landslides. In historic times landsliding on the peninsula has impacted coastal waters, contributing significant quantities of eroded material to the continental shelf and altering the character of the inner shelf. On the Palos Verdes Shelf, eroded material from the landslide has mixed and enlarged a deposit of highly contaminated solids discharged from the Whites Point outfall of the Joint Water Pollution Control Plant (JWPCP). The JWPCP processes waste-water influent from Los Angeles County. This report documents the

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influence of landsliding on coastal waters of the Palos Verdes Shelf and the interaction of the eroded landslide detritus and the effluent-affected sediment layer (EASL).

Historic sedimentation on the Palos Verdes Shelf is strongly influenced by two sources: (a) detritus eroded from the toe of Portuguese Bend landslide, and (b) effluent issued from the White's Point sewage diffusion pipes (Ehlig, 1982; Kolpack, 1987) (Fig. 1). Effluent discharged from the outfall prior to 1972 was heavily contaminated with the pesticide DDT and other contaminants. Damages to the natural resources of Southern California from the discharge of these contaminants was the basis for a large decade-long environmental lawsuit brought by the Department of Justice (DOJ) against the industrial dischargers of the contaminants. This paper synthesizes results prepared for the DOJ to document the history, sources, and magnitude of recent sedimentation on the shelf, and to assess basic geotechnical properties of the EASL deposit mantling the shelf and slope. Information on the Portuguese Bend landslide and Whites Point outfall material is synthesized from available published reports, and testing performed on samples collected by the United States Geological Survey (USGS) during 1992 and 1993. Together, these data identify two depocenters of effluent-affected sediment; one at, and immediately northwest of the Los Angeles County Sanitation District (LACSD) diffuser pipes, and a second offshore Portuguese Bend. The first depocenter is composed largely of effluent emanating from the diffuser array. The second depocenter is a

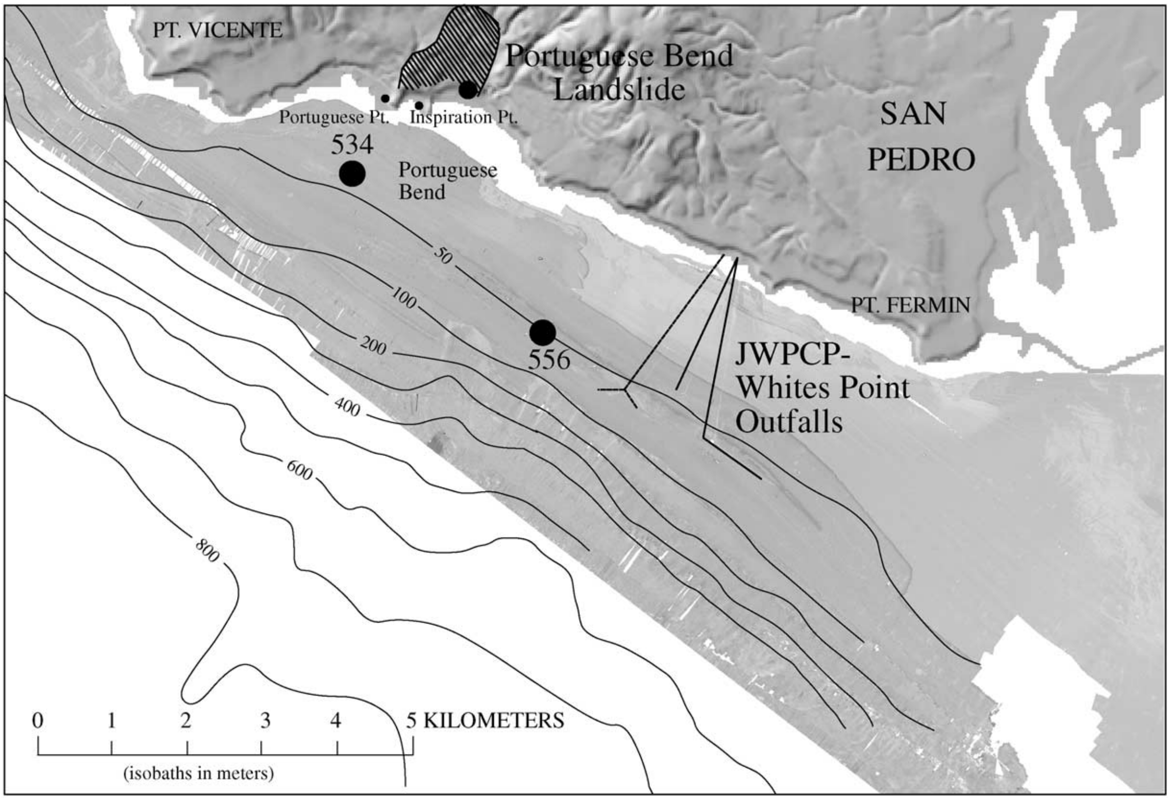

Fig. 1. Map of the Palos Verdes Shelf. The Portuguese landslide (hatchered) is located onshore. Two sampling stations for mineralogy are located, as is the Whites Pt. outfall. The underlying image is a backscatter mosaic of the Palos Verdes margin recorded with a multibeam sonar system (Gardner et al., 1998). The light colored high backscatter in the inner shelf is probably associated with coarser grained material moving southeast in the littoral cell.

mixture of the LACSD effluent discharge and debris eroded from the toe of the Portuguese Bend landslide. This mixing results in a localized enlargement of the EASL with diminished contaminant levels, probably the result of dilution by the Portuguese Bend debris.

2. Portuguese Bend landslide: movement and toe erosion

Although the Portuguese Bend landslide is an ancient feature, the recent historic movement of the slide is the result of municipal and residential changes in land use. The Portuguese Bend landslide comprises 1.06 km^2 of the southwestern portion of the Palos Verdes Peninsula (Fig. 1). The landslide is composed of a tuffaceous unit of the Altamira Shale, a marine member of the Monterey Formation, as well as thick layers of more resistant dolomite (Ehlig, 1992). This portion of a much larger ancient landslide was re-activated in 1956 by the placement of an embankment for a road in the town of Rancho Palos Verdes that was being extended from the crest of the Palos Verdes Hills toward Palos Verdes Drive South near the shoreline.

During construction, over 20 m of fill were placed in sections of the road to elevate the roadbed. The fill destabilized the ancient landslide mass by increasing the downslope shear stress (Ehlig, 1982). Rapid loading of fill might also have had the effect of elevating pore water pressures in the slope, although pressures were not recorded in 1956 and it is not known whether they contributed to the initiation of the landslide. At the time of initiation of the landslide, groundwater conditions in the landslide were somewhat elevated by residential landscaping practices (Ehlig, 1992). Within several months, the landslide enlarged westward of Inspiration Point to include a wedge between that rock headland and the adjacent headland to the west, Portuguese Point (Fig. 1). Movement has destroyed 130 homes, which amounted to 81% of the total residential building stock on the landslide mass (Ehlig, 1992). The landslide mass near its toe is 1070–1100 m wide. Since the landslide was reactivated in 1956, the landslide has traveled, on average, some 150–175 m down slope into the ocean, although some higher portions of the landslide have traveled almost twice as far.

Unusually heavy winter rainfall, beginning in 1978, accelerated movement of the Portuguese Bend landslide and initiated movement of the adjacent 0.32 km^2 Abalone Cove landslide (Ehlig and Bean, 1982). In 1980, efforts to stabilize the Abalone Cove landslide focused on lowering the ground-water table by pumping from wells located within the landslide mass. These efforts led to a significant slowdown in the rate of movement of the Abalone Cove landslide, even during winters of intense rainfall. In 1984, a similar dewatering effort was adopted at Portuguese Bend landslide, but the practice was initially less effective than at the Abalone Cove landslide site. According to Ehlig (1992), the limited effect of the initial set of dewatering wells was due to the lower permeability of Portuguese Bend landslide material, relative to that of Abalone Cove. A second set of wells was installed to improve the flow rate of the dewatering effort. The additional pumping was coordinated with re-grading of portions of the Portuguese Bend landslide to remove basins and depressions that caught water and increased ground water recharge. Installation of surface drains aided in diverting a portion of the storm runoff into the ocean. However, some of the surface runoff still enters fissures within the landslide and partly recharges the groundwater levels of the Portuguese Bend landslide. Nevertheless, the re-grading and second set of dewatering wells were largely successful at significantly reducing movement of the landslide from the high rates of the early 1980s.

Protective wire-mesh gabions were placed at the toe of the landslide in 1988 to protect the mass from wave erosion. The storms of 1989 damaged and destroyed much of this protective barrier, as has subsequent corrosion of the wire. Rainfall during the mid-late 1990s, was heavy, due in part to the El Nino event of 1998. The 7 year period from 1992 through 1998 had the fourth highest rainfall in the 121-year history of Los Angeles. During this period of intense rainfall, the Portuguese Bend landslide accelerated to a rate of movement as great as had occurred during the

1962–1976 period, but never attained the high rates of movement that occurred during the prior intense rainfall period of late 1970s through mid 1980s. This success is directly due to the mitigation efforts taken to lower the water table in and around the landslide.

Currently, in 1999 and 2000 landslide movement is rapidly decelerating from its peak during the El Niño year of 1998. The Army Corps of Engineers is presently assessing a variety of mitigation solutions to provide a protective stabilizing structure at or near the toe of the landslide mass. More detailed accounting of the geology, landslide history, and mitigation efforts can be found in the papers of Ehlig (1982, 1992) and Vonder Linden and Lindvall (1982).

3. Margin sediment from White's Point outfall

Discharge of suspended solids from the Whites Point diffusion pipes began in 1937 and increased steadily until late 1970, when the daily concentration of solids in the fluidized discharge averaged over 400 mg/l (Fig. 2). In 1971, the JWPCP system began partial secondary treatment of sewage. Since then, the discharge of suspended solids has diminished significantly.

The cumulative weight of suspended solids discharged from the system was determined by integrating the discharge curve (Kolpack, 1987). The estimated total discharge by weight for the period of 1937–1987 is 4.0 million metric tons (Mmt), and the estimated discharge by volume is 7.3 million cubic meters (Mm^3). It is not known how much material discharged from the outfall survives the process of decomposition in the water column and is actually deposited on the seafloor, or what additional natural organic material is deposited with the effluent deposit. We used these estimates to represent the amount of material directly discharged from the diffuser pipes and deposited on the Palos Verdes Shelf.

4. Margin sediment from Portuguese Bend landslide

Seafloor sediment derived from Portuguese Bend landslide is found seaward of the wave-eroded landslide toe. Subaerial deformation of the landslide material, as it is transported from the uplands toward the ocean, heavily weakens the landslide such that only moderate wave action is needed to erode the landslide toe. Other landslides along the margin at Abalone Cove and Pt. Fermin have contributed relatively insignificant amounts of material to the shelf (Ehlig, 1982).

Storm-wave energy that erodes the landslide toe typically comes from the west and southwest,

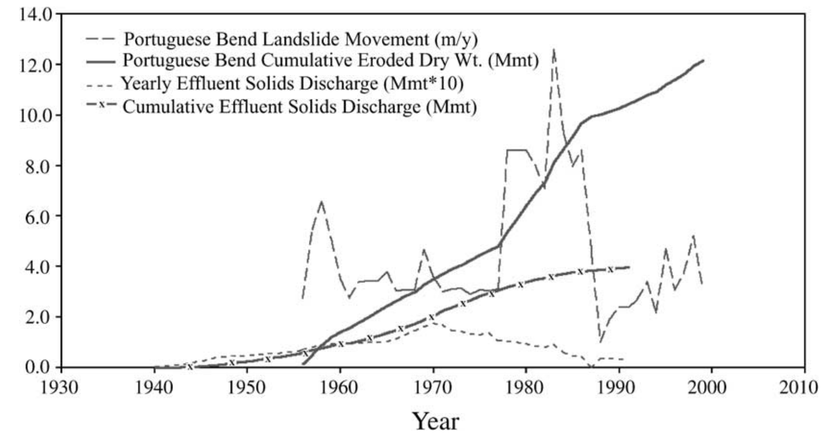

Fig. 2. The annual movement (m/yr) of the PBL toe and cumulative dry weight of eroded material in millions of metric tons (Mmt). Also, the annual and cumulative solids discharge for the JWPCP outfall, integrated from suspended solids.

although large waves from the southeast do occasionally impact the shelf (Noble, 1994). Catalina Island, to the south, acts to reduce the impact of strong southerly waves on the coastline of the Palos Verdes Peninsula, and the Portuguese Bend landslide. Nevertheless, erosion of the landslide toe has been continuous and persistent. Often during periods of moderate wave action, a visible plume of eroded material typically clouds the surface waters of the inner-shelf region of Portuguese Bend. The littoral drift carries material along the inner shelf south eastward from the toe of the slide towards Point Fermin (Fig. 1), counter to the predominant mid- and outer-shelf currents (Noble et al., 2002). Some storms have caused severe and rapid erosion of the toe of the landslide, as well as to other parts of the coast. During the January and March storms of 1983, for example, the toe of the landslide retreated 15 m and contributed some 0.65 Mm^3 of material to the sea (Kayen et al., 1994). These storms also eroded an additional 1.5–2.3 Mm^3 of material from adjacent areas of the coast, which had been deposited at the base of the cliffs as rockfall and beach sand.

Rates of landslide movement do not necessarily equal rates of erosion at the toe: the balance of the downslope movement and erosion at the toe will result in an advance or retreat of the landslide into the ocean. The volume and mass of landslide material eroded from the Portuguese Bend landslide and deposited on the shelf were estimated indirectly from the movement of survey monuments positioned on the landslide mass. The rates of movement of the Portuguese Bend landslide into the ocean were estimated by averaging survey monument movements made on the landslide and accounting for compression effects of the landslide toe. Placement and measurement of the survey monuments were performed by the Los Angeles County Surveyors Office.

Rapid advances and retreats of landslide in the ocean have occurred over short time periods. However, during the period of movement from 1956–1999, erosion at the toe has largely kept pace with the downslope movement of the landslide, such that the shoreline position today is essentially unchanged from that of 1956 (Kayen et al., 1994). In this sense, the erosion of a sub-aerial landslide entering the surf zone can be viewed as analogous to the wasting of a tidewater glacier by wave and calving processes.

The reported horizontal accuracy of these measurements is on the order of one-one hundredth of a meter. To obtain an estimate of the volume of material per year contributed to the ocean by the landslide, we multiplied the rate of landslide movement by the shore-parallel landslide cross section area. The height of the wave-eroded front of the landslide varies along the length of the mass, and has varied in time. Measurement of the height of the landslide near the surf zone is less certain then the horizontal monument surveys. We used available elevation data and a cross section drawing of the landslide at the toe developed by Ehlig in an unpublished memoranda to the City Manager of the Town of Rancho Palos Verdes. From these data we estimate that the average height along the landslide front for the period of 1956 to the present is 35 m and may have varied as much as 5 m (15%) over the period of movement. Integrating the movement of the slide mass we estimate that, since 1956, approximately 7.6 Mm^3 of material, ± 1.0 Mm^3, has been introduced onto the Palos Verdes Shelf from toe-erosion of the landslide. This volume of material has a weight of approximately12.1 Mmt, ± 1.7 Mmt, given the average dry-bulk density of the eroded material and uncertainties in the eroded volume. The dry weight of the eroded landslide material was estimated based on an average specific gravity of 2.67 from samples of the landslide material collected in 1992, and an average dry-bulk density of 1.59 g/cm^3.

5. Mixing of landslide and effluent-affected shelf sediment: mineralogy

Bottom sediment samples from the Palos Verdes Shelf were assessed for mineralogic composition using X-ray diffraction (XRD) to help determine the relative contribution of sediment from onshore sources (i.e., from the landslide). Onshore samples were taken from the toe of the landslide in 1992 (Station 8, Wong, 2002). Offshore samples were taken from native pre-effluent sediment from (1) vibracore 7A1 (USGS Station 556 near LACSD station 6C; Lee et al., 2002); (2) effluent-affected sediment from box core 204 (USGS Station 556); and (3) sediment from box core 220 (USGS Station 534, between LACSD stations 4C and 4D; Lee et al., 2002), directly seaward of the landslide. Samples tested at the USGS were powdered and then exposed to bleach to remove volatile organic matter following the methods of Gaffey and Bronnimann (1993). Samples were mounted to glass slides by suspending the particles in fluid and allowing the powdered grains to settle in a random orientation, as the fluid evaporated. The XRD results are compared with an independent study by the Vantuna Research Group (Occidental College), contracted by the United States Army Corps of Engineers (USACE) in 1992.

The mineral composition of the bottom sediment at stations 204 and 220 are presented in Table 1, along with those of the USGS and USACE onshore samples taken from the landslide mass. The compositions of the samples are similar and are a mixture of dolomite, clay minerals, and zeolite group minerals, the latter of which are commonly associated with the alteration of volcanic parent material. The mineral assemblages from both core samples and the landslide mass contain the composition of the marine sedimentary units of the Altamira Shale, a member of the Monterey Formation of middle Miocene age. The mineralogy of both the landslide sample and the samples from within the effluent-affected sediment layer are nearly the same. This supports the findings of Wong (2002) that detritus from the Altamira Shale has mixed with the effluent-affected layer.

Further evidence of mixing of the effluent-affected layer and detritus eroded from the landslide are discussed by the USACE (1992). In that report, it was noted that samples collected throughout the inner shelf have an oxidized surface sediment layer ranging in color from brown to tan, suggesting recent sedimentation from a terrigenous source. Together, the USACE diffractograms and the reported oxidized surface of the Vantuna grab samples suggest rapid, recent deposition by surf zone erosion of the Portuguese Bend landslide.

Our data are in agreement with that of the USACE, indicating that the mineralogical

Table 1
USGS and USACE bulk sample XRD mineralogy for Portuguese Bend landslide and Palos Verdes Shelf sediment

Mineral	Portuguese Bend LS USACE sample	Portuguese Bend LS USGS sample	Pre-effluent sediment (7A1) USGS sample	Core-220 USGS sample	Core-204 USGS sample
Quartz	Present	Moderate	Moderate	Moderate	Major
Plagioclase	Present	—	Major	Major	Major
Dolomite	—	Major	Minor	Moderate	Moderate
Pyroxene	—	Minor	Moderate	Moderate	Moderate
Illite	Present	Moderate	Moderate	Minor	Moderate
Smectite	Present	Moderate	—	Minor	Minor
Zeolite grp.—Phillipsite	Present	—	Minor	Minor	Moderate
Zeolite grp.—Clinoptilolite	—	Minor	Minor	Minor	Minor
Zeolite grp.—Chabazite (non-marine)	—	Minor	Minor	Minor	Minor
Zeolite grp.—Stilbite (non-marine)	—	—	Minor	—	Minor
Calcite	Present	—	Minor	Minor	—
Amphibole	Present	—	Minor	Minor	Minor
Halite	Present	—	Minor	Minor	Minor
Chlorite	—	—	—	—	—

Major, $>25\%$ of composition; moderate, 5–25% of composition; minor, $<5\%$ of composition.

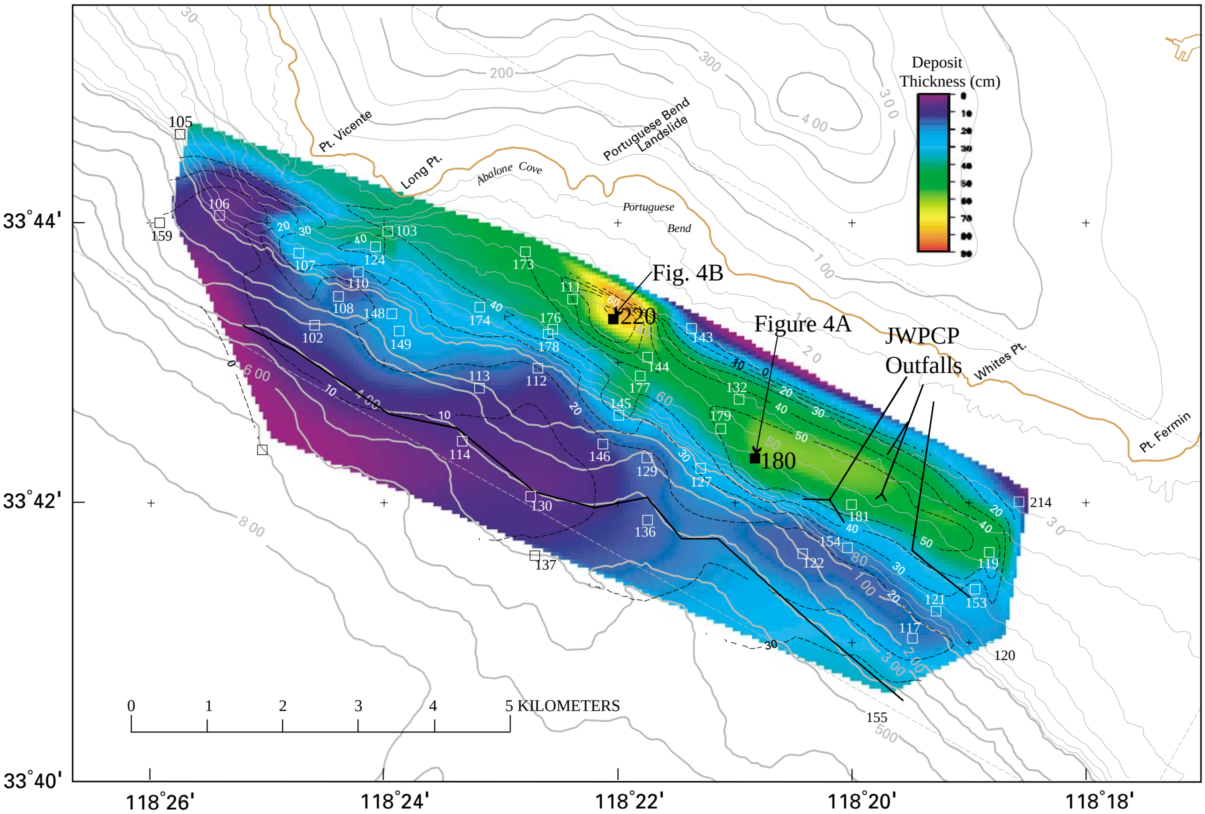

Fig. 3. Isopach map of the effluent effected sediment deposit.

component of the Portuguese Bend landslide and offshore core samples in the effluent-affected layer are similar. In particular, the abundance of dolostone-related minerals in the Portuguese Bend landslide and in the core sediment strongly links the eroded material from the landslide with the mineral component of the effluent-affected sediment layer.

6. Mixing of landslide and effluent-affected shelf sediment: density profiles

We made an assessment of the thickness of the EASL, based on *p*,*p*-DDE profiles and profiles of sediment bulk density for USGS cores (Lee, 1994; Kayen et al., 1994). Chemical analyses were obtained through a contract laboratory (Lee, 1994). Whole core sediment samples recovered from the Palos Verdes Shelf and slope were logged for bulk density on the USGS multi-sensor whole core sediment-logging device using the methods of Kayen et al. (1999). Sealed cylindrical sediment cores were placed horizontally upon a transport sled and moved by a computer-controlled stepper motor. Cores pass through an instrument frame supporting a scintillation counter and a vessel emitting a 1-cm columnated beam of gamma rays from a radioisotope Cesium-137 source. Sediment bulk is estimated from the gamma-ray attenuation characteristics of the cores according to Lambert's law (For further discussion, see Kayen et al., 1999).

An isopach map of the EASL is presented in Fig. 3, based on the density logs and estimated sediment thickness. A broad, elongate center of

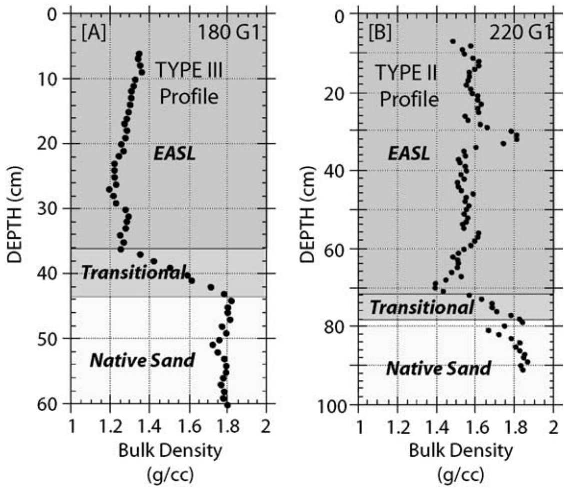

Fig. 4. Density Logs for Types II and III material.

deposition occurs in the region proximal to the outfall array (Hampton et al., 2002; Murray et al., 2002; Lee et al., 2002). An example of a density and p,p'-DDE profile through the central axis of this deposit, near the diffuser array is shown in Fig. 4a. This profile, termed Type III has a clearly defined EASL zone in the upper section of the density log. The Type III profile has a low density zone near the surface that drops to a minimum density (1.2–1.3 g/cm^3) at depth corresponding with a maximum organic content (Lee et al., 2002). Deeper in the section, the density rises rapidly to a value near 1.8 g/cm^3 suggestive of native, pre-outfall, sediment. The geometry of this deposit and the distribution of DDT and DDE, therein, are discussed in detail in companion papers in this volume (see Hampton et al., 2002; Murray et al., 2002; Lee et al., 2002).

A second center of deposition is located offshore Portuguese Bend landslide. A profile of sediment bulk density for a gravity core taken during the USGS cruise in 1993 that penetrated through the second depocenter (220G1) is presented in Fig. 4b. This profile was termed Type II (Lee et al., 2002), and is typical of sediment within the transition zone between the well-defined EASL-axis sediment of the mid-shelf (Type III) and denser, sandy inner-shelf material (Type I). The Type II sediment shows a relatively low density of approximately 1.5–1.6 g/cm^3 throughout most of the upper portion of the sediment column. Below a sharp transition zone between 70 and 75 cm is denser sandy sediment that, like the Type III profile (Fig. 4a), is suggestive of native pre-outfall deposits. From the isopach map presented in Fig. 3, constructed from downcore profiles of density and p,p'-DDE, we believe that the EASL is locally thickened offshore Portuguese Bend. We believe this thickening is due to mixing of outfall material and detritus eroded from the toe of the landslide.

Using the density and DDE profiles to determine the transition from anthropogenic to native sediment, and thus the thickness of the effluent-affected sediment layer, the profiles were then used to compute the mass accumulation on the shelf and upper slope. We assumed a grain specific gravity of 2.65 for the sediment and converted the saturated bulk density profiles to profiles of dry density (seawater removed) and integrated the total mass of effluent-affected sediment within each core. Fig. 5 presents the spatial distribution of mass in the EASL. As in Fig. 3, this plot shows a deposit that has an along-shelf axis of maximum mass accumulation centered between the 40 and 50 m isobaths. The low bulk density of effluent-affected material near the outfall leads to a less pronounced central axis of the deposit proximal to the discharge center, relative to the axis in Fig. 3. In contrast, the region offshore Portuguese Bend shows a dramatic increase in the mass accumulation relative to the surrounding EASL. This increase is probably due to mixing of the low-density effluent and higher density eroded landslide material. For example, the upper portion of the Type II profile in Fig. 4 is approximately a half-and-half mixture of effluent and eroded Portuguese Bend material given end member bulk densities for these two materials.

7. Bathymetric change

To assess the magnitude of the historic accretion of sediment derived from the Portuguese Bend landslide on the inner shelf, we compared bathymetric surveys from 1933 and 1976 performed by the National Ocean Survey (NOS, formerly the United States Coast and Geodetic Survey,

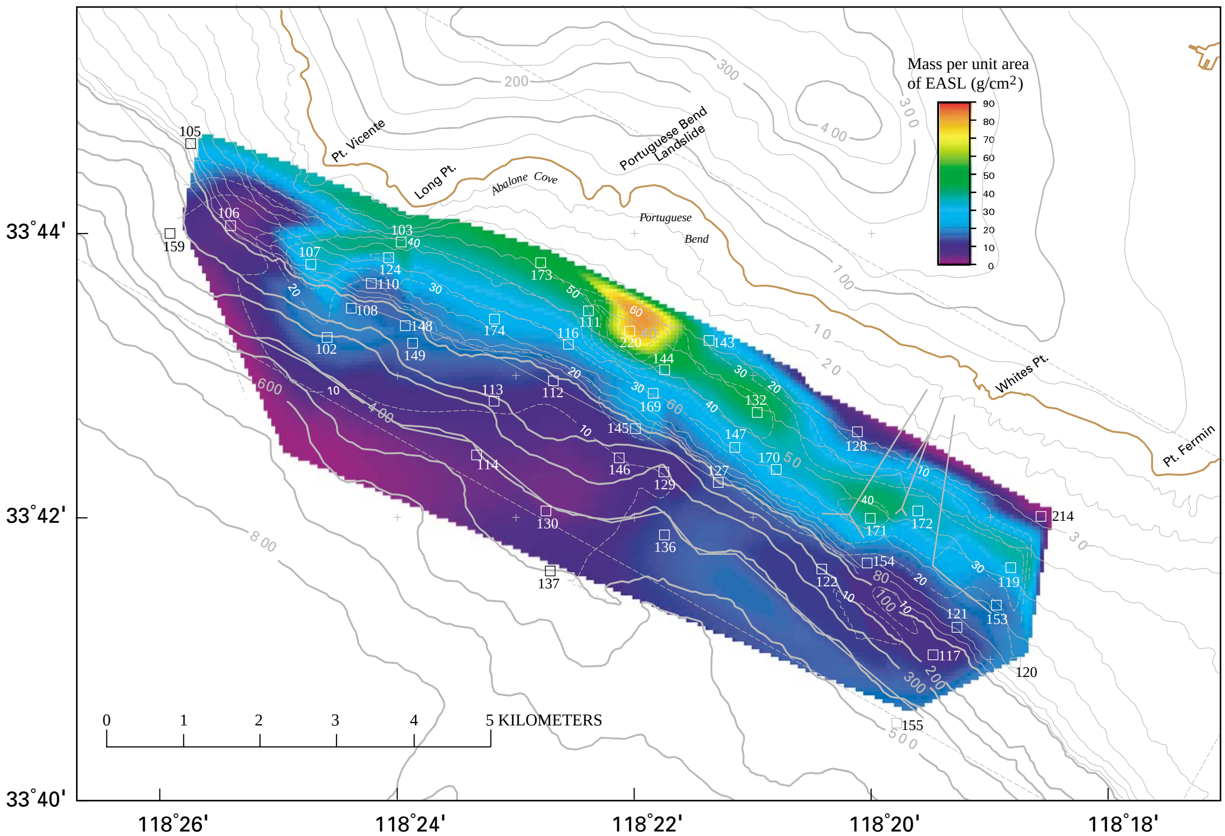

Fig. 5. Mass accumulation of EASL on the Palos Verdes margin.

USCGS). The NOS surveys are, in general, high quality detailed soundings of seafloor bathymetry with a high sampling density (Jaffe et al., 1991). The 1933 survey was performed with lead line techniques before the movement of the landslide, when the inner shelf was largely dominated by a rock outcrops and kelp beds.

The 1976 survey, performed using echo-soundings techniques, determined the inner-shelf bathymetry when approximately 51% of the total landslide movement into the ocean (up to 1999) had occurred, as estimated by the monument movements. The two surveys are tied to a common geographic datum, the North American Datum of 1927 (NAD27). After completion of the two surveys, NOS data processing procedures remove tidal fluctuations and the effects of wind and air pressure. Accurate tidal data are available for this portion of the coastline, due to the proximity of the Palos Verdes Shelf to Redondo Beach, San Pedro Harbor, and Port of Los Angeles.

We used the Geographic Information System software program ARC-INFO™ to subtract the 1933 survey from the 1976 survey, such that a difference map could be constructed, largely attributable to sediment volume change on the inner-shelf (Fig. 6). The difference map is a measure of the net change in bathymetry between the surveys. There are artifacts in the difference map that are a product of the gridding technique. These artifacts include the linear-beaded texture of the deposition/erosion zones, which occurs when

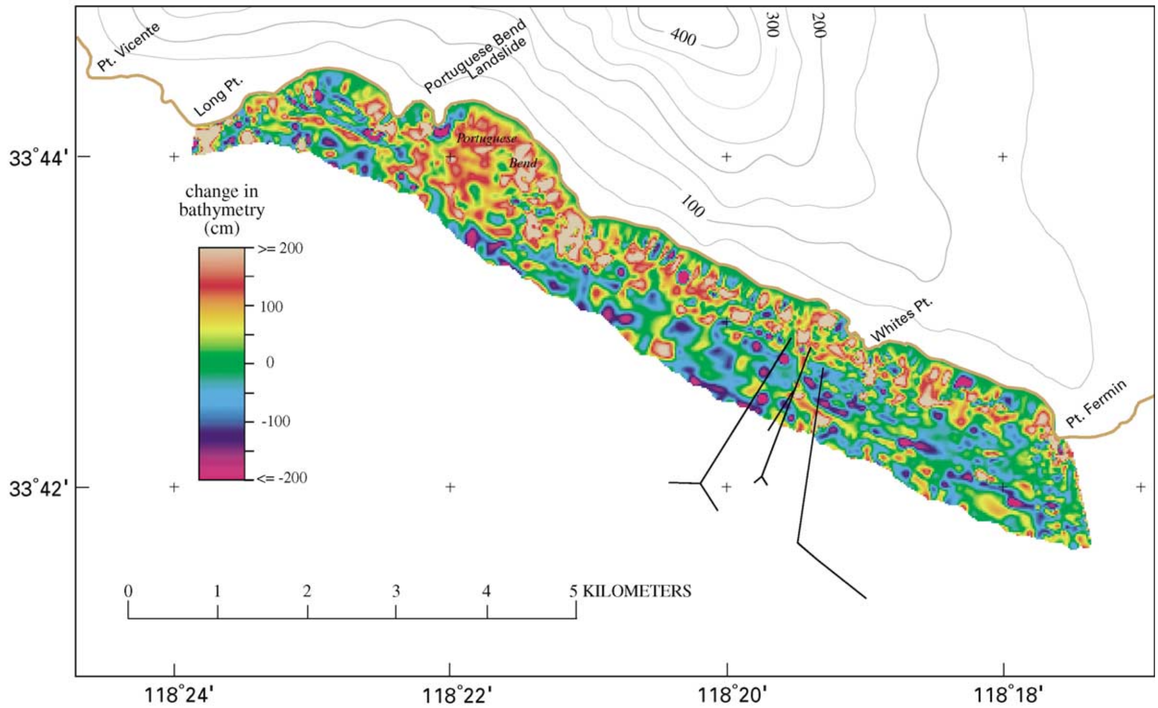

Fig. 6. Bathymetric difference map for NOS 1933 and 1976 surveys. In this display, red areas represent zones of bathymetric depth decrease (seafloor rising, water column shoaling), grading continuously to blue–purple zones that indicate bathymetric depth increase (seafloor lowering, water column deepening).

differencing oblique bathymetric grids. We did not remove any apparently spurious point data to preserve any random error associated with the bathymetric surveys.

Survey monuments on stable portions of the peninsula indicate that this shoaling is not the result of tectonic uplift of the shelf. Rather, based on the hydrographic surveys, The inner-shelf difference map largely presents a zone of sediment accretion. The main lobe of bathymetric decrease (shoaling) between 1933 and 1976 is in Portuguese Bend near the landslide toe, indicated by the large red zone south of the bend (Fig. 6). The difference map suggests that a portion of the material eroded from the landslide toe by waves resides within the inner-shelf region, inshore of the principal effluent-affected sediment deposit. The axis of the bathymetric shoaling eastward of Portuguese Bend occurs between roughly the 5- and 15-m isobaths, suggestive of alongshore transport of sediment on the inner shelf. We integrated the bathymetric difference map and estimated a bathymetric volume change in the inner-shelf of 3.7 Mm^3 landward of the 30 m water depth. We attribute the volume change largely to the accretion of sediment eroded from the toe of the Portuguese Bend landslide. We note that, based on the monument data of Ehlig (1992), between 1956 and 1976, an estimated 2.9 Mm^3 of material ($\sim$4.6 Mmt) was eroded from the landslide, 78% of the bathymetric change we integrated from the NOS surveys.

Between 1976 and 1999, monument data indicate an additional 4.7 Mm^3 ($\sim$61% of the total landslide material eroded between 1956 and 1999) slid into Portuguese Bend. The total volume and mass of material eroded from the toe increased from 2.9 Mm^3 and 4.6 Mmt, respectively, in 1976, to 7.6 Mm^3 and 12.1 Mmt in 1999 (Fig. 7). We do not know how much of this material still resides on the inner shelf. El Niño storms following the 1976 bathymetric survey were large and may have

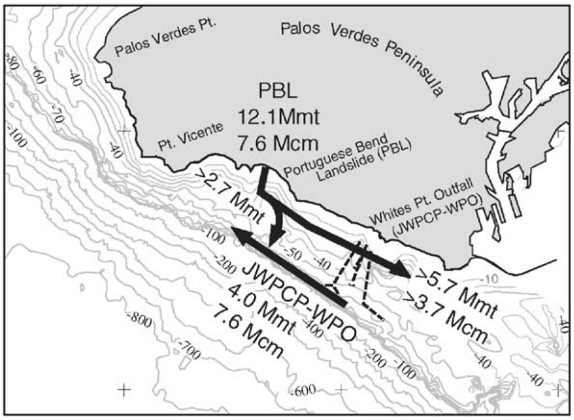

Fig. 7. Estimated contribution of sediment on the Palos Verdes Shelf from Portuguese Bend landslide (PBL) and Whites Point outfall (JWPCP–WPO) effluent discharge. The curved line represents the estimated fine particle contribution by eroded Portuguese Bend landslide material to the effluent effected sediment layer.

eroded material from the inner-shelf. Based on the total sediment contribution by the landslide from 1956–1999, and our estimate of bathymetric volume change in the inner-shelf, we estimate that the present volume and dry weight of sediment that is derived from the landslide and resident on the inner-shelf exceeds 3.7 Mm^3 and 5.7 Mmt (48% of landslide input). This contribution may be as large as 6 Mm^3 and 9.4 Mmt (78% of landslide input) (Fig. 7).

8. Conclusions

In this paper we document the volume and mass of sediment contributed to the Palos Verdes Shelf by the Whites Point outfall and Portuguese Bend landslide. The principal source of recent sediment deposited on the inner-shelf, in terms of mass, is the Portuguese Bend landslide. Much of the landslide material contributed to the shelf is still resident in the inner shelf, with the remaining sediment (predominantly silt and clay), available to the mid- and outer-shelf, and slope, or has bypassed the Palos Verdes margin entirely. From 1937–1987, it is estimated that 4.0 Mmt (7.6 Mm^3) of solid anthropogenic effluent was discharged into the water column and onto the Palos Verdes Shelf (Fig. 7).

We estimate that Portuguese Bend landslide-derived sediment trapped in the inner shelf and transported predominantly east–southeast to be in excess of 5.7 Mmt (3.7 Mm^3) and possibly as much as 9.4 Mmt (6 Mm^3). The material outward of the inner shelf that either resides on the shelf EASL, or has bypassed the shelf entirely, is estimated to be at a minimum 2.7 Mmt. Mineralogic data clearly indicate that landslide material has mixed with the mid- and outer-shelf EASL.

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